4.1 GENERAL

Detention basins that receive storm runoff, but that have negligible losses through infiltration, must rely principally on sedimentation processes for pollutant removal. Under some conditions, and to some extent, reductions attributable to other processes may influence removal of specific pollutants (e.g., natural die-off of coliform bacteria, and algal uptake of soluble nitrogen and phosphorus).

Of the variety of configurations and operational modes that have been used, stormwater detention basins that maintain a permanent pool of water, often referred to as "wet ponds," are generally considered to be the most effective for pollutant reduction.

Nine such devices in various parts of the county were actively monitored during the NURP program, as the local agencies' choice of a preferred control approach.

This section presents a procedure for projecting performance of such devices, and a comparison of results with observed performance of the NURP detention basins. A wide variety of concepts and configurations is represented by the wet ponds that were studied, ranging from oversized storm drains to natural ponds and small lakes. The size of the devices relative to the contributing drainage area varied over a wide range; the common elements for all were the maintenance of a permanent pool of water and sedimentation as the principal pollutant-removal mechanism.

The input data requirements for analysis of sedimentation devices are essentially the same as for recharge devices described in the previous section, but with the following exception. In this case the "treatment rate" is determined not by soil percolation rates, but by the settling velocity of the particulates present in the urban runoff. Represenative values for settling velocity can be assigned to urban runoff on the basis of a significant number of settling column tests conducted during the NURP program.

4.2 ANALYSIS METHOD

The probabilistic computations and performance curves presented in Section 2 can be applied to wet ponds (with appropriate adaptation and interpretation) to reflect the nature of the treatment process that occurs in detention basins of this type.

A basic aspect of such a system is that part of the time (while runoff inflows occur), stormwater is moving through the basin, and sedimentation takes place under dynamic conditions. During the considerably longer dry periods between storm events, sedimentation takes place under quiescent conditions.

4.2.1 Removal Under Dynamic Conditions

Characterization of the performance of sedimentation devices has been extensively analyzed over the years because of the important role such devices play in both water treatment and wastewater treatment systems. A method of analysis which is particularly suitable is presented by Fair and Geyer (5). Removal due to sedimentation in a dynamic (flow through) system is expressed by the following equation:

$$R = 1 - \left[1 + \frac{1}{n} \cdot \frac{v_s}{Q/A} \right]^{-n} \qquad (8)$$

where:

R = fraction of initial solids removed (R * 100 = % Removal)

v_s = settling velocity of particles

Q/A = rate of applied flow divided by surface area of basin (an "overflow velocity," often designated the overflow rate)

n = a parameter which provides a measure of the degree of turbulence or short-circuiting, which tends to reduce removal efficiency

One value of this model is that it provides a quantitative means of factoring into the analysis an expression for impaired performance due to short-circuiting (since many stormwater retention basins will not have ideal geometry for sedimentation). Fair and Geyer suggest an empirical relationship between performance and the value of "n," which is: $n = 1$ (very poor); $n = 3$ (good); $n > 5$ (very good). In addition, when a value of $n = \infty$ is assigned (ideal performance), the equation reduces to the familiar form wherein removal efficiency is keyed to detention time.

$$R = 1 - \exp\left[- \frac{v_s}{Q/A} \right] \qquad \text{or} \qquad (9)$$

$$R = 1 - \exp\left[- k\, t \right] \qquad (10)$$

where:

k = v_S / h (sedimentation rate coefficient)

h = average depth of basin

t = V / Q residence time

V = volume of basin

The two expressions are equivalent. To use them, one must be able to identify an appropriate value for either settling velocity, or for the rate coefficient (k), which will ultimately depend on the settling velocity of the particulates present.

Solving equation (8) for a range of overflow rates and particle settling velocities and plotting the results as shown by Figure 7, indicates the wide range in removal that can be expected either (a) at a constant overflow rate for particles of different size, or (b) at different rates of flow for a specific size fraction. Both of these variable factors are present in urban runoff applications. The effect of a range of particle settling velocities is addressed by performing separate computations for a number of settling velocities and then using weighted mass fraction to compute net removal.

Storm sequences result in variable overflow rates, each event producing a different average rate, and hence, removal efficiency. The probabilistic analysis procedure described in Section 2.4 (Flow-Treatment), and summarized by the design performance curves in Figure 2, is the relevant analysis to apply. This analysis makes the following assumptions:

- The short-term variability of flows (within storm events) is small compared with the variability of average flows between storms. To the extent that this is not the case, Figure 2 will overestimate long-term performance.

- Storm flows and pollutant concentrations are independent. If flow rate and concentration are negatively correlated (high flows produce lower concentrations), performance will be better than indicated. For positive correlations, performance will be poorer than indicated.

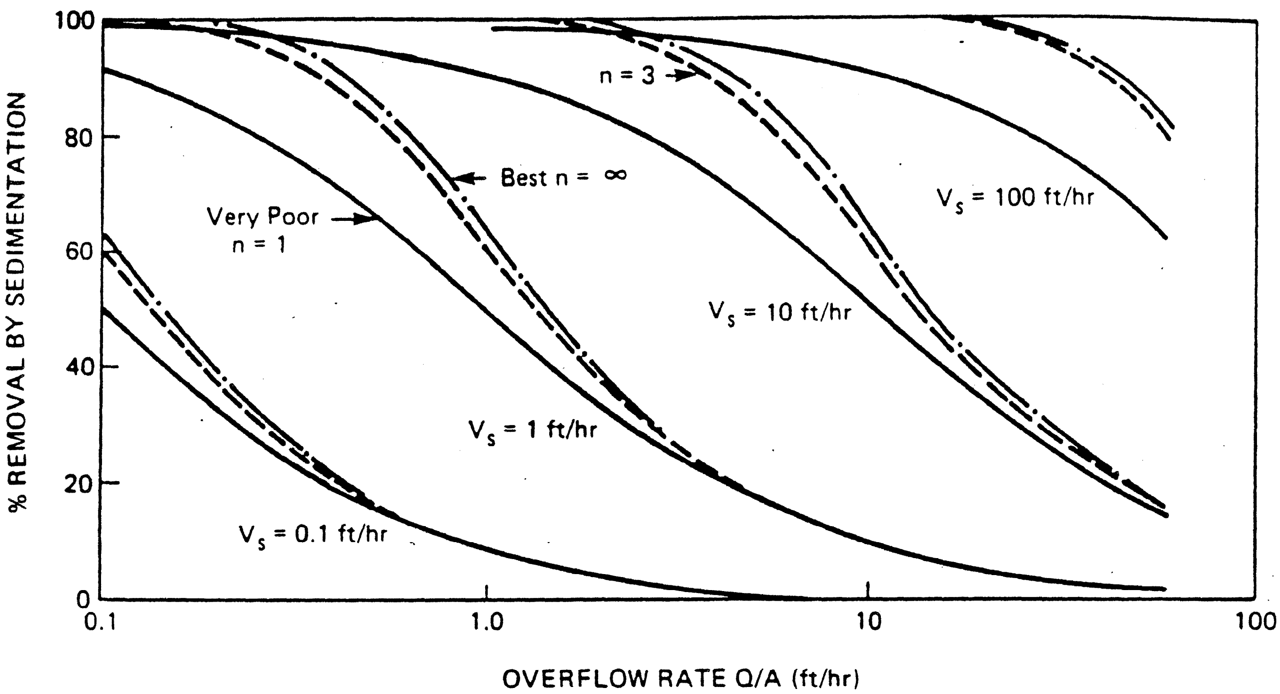


Figure 7. Effect of settling velocity and overflow rate on removal efficiency

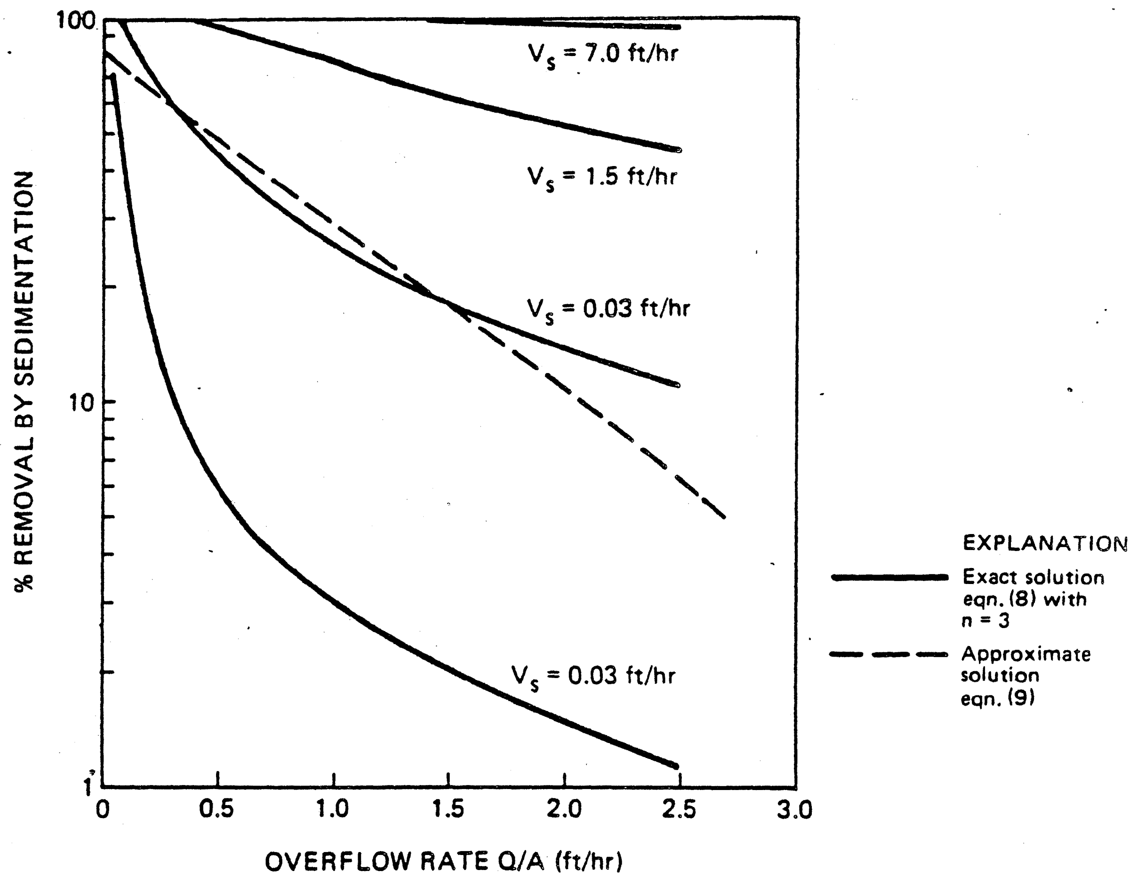


Figure 8. Flow-removal relationships for exponential approximation

- Removal efficiency is an exponential function of flow.

Available data on stormwater retention basins are not suitable to provide empirical estimates of flow rate/removal relationships. The relationship represented by equation (8) has been used instead. Removal fractions for a range of settling velocities representative of urban runoff, as computed by equation (8), are presented in Figure 8 as a semi-log plot on which the exponential approximation, equation (9), would plot as a straight line. For a site-specific analysis (for each settling velocity separately), the straight line approximation would match the exact solution at the point corresponding to the mean overflow rate (QR/A), and the slope would be adjusted to give the best match over the range of rates expected to span the bulk of the important storms. The intercept of this fitted line ($Q/A = 0$) provides the estimate for the factor Z in equation (3). For example, in the sample illustration shown in Figure 9, the overflow rate for the mean storm is 1.5 ft/hr. For the size fraction represented by a settling velocity of 0.3 ft/hr, removal at the mean flow rate (RM) is 0.18 and Z is estimated to be 0.8. Over the range of overflow rates of interest, the exponential approximation is within about 10%.

Long-term average removal of a pollutant under dynamic conditions can, therefore, be estimated from the statistics (mean and coefficient of variation) of runoff flows, basin surface area, and representative particle settling velocities for urban runoff.

4.2.2 Removal Under Quiescent Conditions

For much of the country, the average storm duration is about 6 hours, and the average interval between storms is on the order of 3 to 4 days. Thus, significant portions of storm runoff volumes may be detained for extended periods under quiescent conditions, until displaced by subsequent storm events. The volume of a basin relative to the volumes of runoff events routed through it is the principal factor influencing removal effectiveness under quiescent conditions.

The probabilistic computation described previously in Section 2.5 (Volume-Capture), and summarized by design performance curves in Figures 3 and 4, is used to estimate removals under quiescent conditions. This analysis assumes that physical volumes are removed from the basin during the dry periods between storms, as in the recharge basin analysis presented in the preceding section, where captured volume percolates. However, for sedimentation devices that maintain a permanent pool of water, some modification is required because there is no loss of stored volume between runoff events. Instead, it is the particulates in the detained volume that settle out under quiescent conditions. The modification required is to express this condition in terms of the parameters of the design performance curves.

The term Ω may be thought of as a "processing rate." For a recharge device, it is the rate at which volume is removed from the basin by percolation through the bottom and sides. For a sedimentation device, it may be thought of as a particle removal rate. Using this interpretation, the term $\Omega \Delta$ in equation (7) can be considered to represent that portion of the basin volume from which solids with a selected settling velocity have been completely removed. Instead of the TSS concentration of the entire volume diminishing with time under quiescent settling, the concentration is assumed to remain constant, while the remaining volume with which this concentration is associated diminishes with time. The solids removal rate is then:

$$\Omega = v_s * A \qquad (11)$$

where:

v_s = particle settling velocity (ft/hr)
A = basin surface area (square feet)

4.2.3 Combining Dynamic and Quiescent Effects

The procedures described above can be used to compute separate long-term removal efficiencies under dynamic and quiescent conditions. Since each type of condition prevails in a detention basin at different times, the overall efficiency of a basin is the result of the combined effect of the two processes at work. The simple model used to integrate these effects is illustrated by Figure 9.

Five identical storms with an interval between event midpoints (Δ) of 3.5 days are routed through a basin, assuming plug flow. Each storm has a duration of 12 hours (0.5 day), and a volume which is 25% of the basin volume (VB/VR = 4). The plotted lines track the residence/displacement pattern in the basin for the leading edge, midpoint, and trailing edge of Storm #1. The shading highlights the fraction of the total residence time when dynamic conditions prevail. For this simplified case, and for actual conditions where both storm volumes (VR) and intervals (Δ) fluctuate, the fraction of time under dynamic conditions is estimated by:

Fraction of residence time under dynamic conditions $= D / \Delta$ (12a)

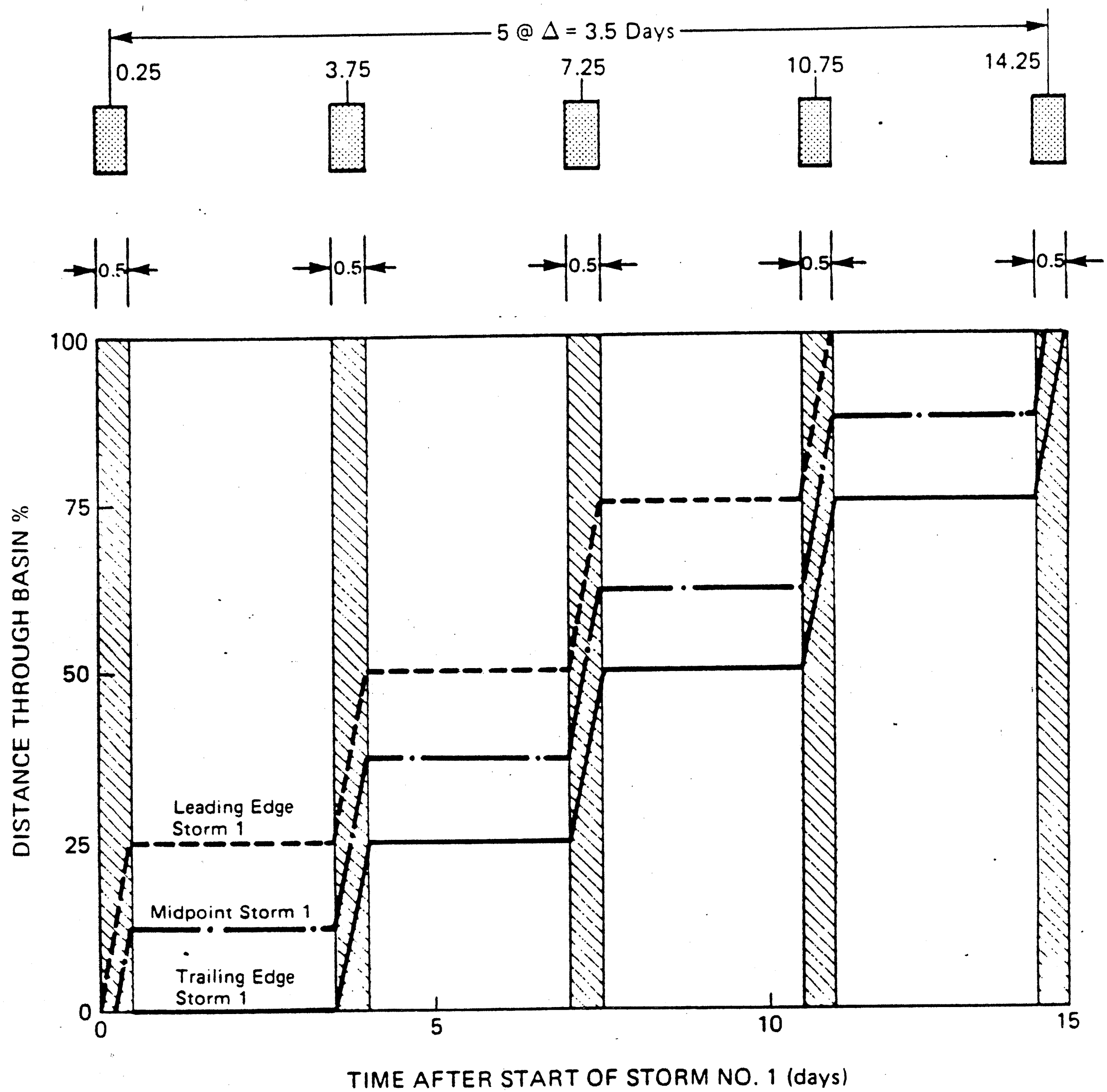
Fraction under quiescent conditions $= 1 - (D / \Delta)$ (12b)

where:

D = mean storm duration
Δ = mean interval between storm midpoints

This simple schematic illustrates several relevant features of the operation of this type of device. When the basin is as large as that indicated (which is not uncommon for current practice), the outflow volume during an event represents a different parcel of water than that for the storm that causes it to be displaced. Assessing performance by comparing paired influent and effluent loads for individual storms is less appropriate than the comparison of overall influent and effluent loads for a long-term sequence of storm events.

All runoff volumes which enter the basin undergo the dynamic removal process one or more times before discharge. For the large basin illustrated, this is broken up into four different periods of displacement. For a basin with a volume small enough that the runoff passes all the way



For Storm Midpoint Volume

Total Residence Time = 14.0 Days

Dynamic Time: (0.25) + (3 x 0.5) + 0.25 = 2.0 Days   2/14 = 0.14

Quiescent Time: 14.0-2.0 = 12 Days   12/14 = 0.86

$D/\Delta = 0.5/3.5 = 0.14$
$(1-D/\Delta) = 0.86$

Figure 9. Illustration of quiescent vs. dynamic residence time in a storm detention basin

through, there would be only one such period of dynamic removal. Performance efficiency is affected simply on the basis of the "overflow rate" that the basin size provides.

The quiescent removal process then operates on (a) those portions of the total runoff volume that remain in the basin during the dry interval that follows an event, and (b) on that fraction of the influent pollutants that remain in the water column after operation of the dynamic process. In the situation illustrated, the average runoff volume is exposed to four different periods of quiescent settling, amounting to an extended period under this condition. In a very small basin, the relative effect of the quiescent removal process may be insignificant, simply because such a small fraction of the total runoff remains in the basin at the end of each storm.

The removal efficiency for the basin under the combined effect of both dynamic and quiescent processes can be computed by applying the removal efficiency of either the dynamic or quiescent process to the pollutant fraction remaining after the operation of the other. If the fractions not removed by the dynamic and quiescent processes operating independently are f_D and f_Q, respectively:

$$\text{COMBINED \% REMOVAL} = 100 [1 - (f_D * f_Q)] \qquad (13)$$

It should be noted that in the larger basins, either process operating alone will be capable of high degrees of removal. One might consider the quiescent process to be the dominant one in large basins, because high particulate reductions can be produced even if there were no removal during dynamic periods, and because the quiescent periods provide the conditions in which the removal processes other than sedimentation can come into play. In small basins, the dynamic process will be the dominant one because only small fractions of the runoff will remain in the basin subject to the quiescent process.

4.3 VALIDATION

Performance data from nine wet pond detention basins monitored during the NURP program have been analyzed and used to test the reliability of the probabilistic methodology. These devices cover a wide range of physical types, and also provide a wide range of basin sizes relative to the contributing urban drainage area.

For the calibration effort, monitored data on storm runoff rates and volumes entering a detention basin are analyzed to define their statistical characteristics. For long-term performance projections, long-term rainfall records for the area in question are used, and the statistical properties of runoff are estimated from the rainfall record. The settling velocity of particulates in urban runoff is estimated from data obtained from settling column tests performed by a number of the NURP projects.

In addition to producing a fairly extensive data base on pollutants entering and leaving detention devices, another critically important contribution of the NURP effort was data to support estimates of the settling velocity of particles in urban runoff. Any analysis methodology for sedimentation, including that adopted for this analysis, requires information of this nature for use either directly (equation 8) or in surrogate form, as with a reaction rate (equation 10).

4.3.1 Settling Velocity of Particles in Urban Runoff

Settling tests were conducted by a number of NURP projects on samples of urban runoff. Results from these tests, and from a similar set of tests reported by Whipple and Hunter (7), have been analyzed to derive information on particle settling velocities in urban stormwater runoff. The analysis procedure used for reducing settling test data and a detailed discussion of the overall analysis results, which are summarized briefly below, are presented in the Appendix.

The analysis of 46 separate settling column tests indicates the following:

- There is a wide range of particle sizes, and hence settling velocities in any individual urban runoff sample.
- The distribution of settling velocities can be adequately characterized by a log-normal distribution.
- There is substantial storm-to-storm variability in median (or other percentiles of) settling velocity at a specific site. The range indicated is about one order of magnitude in observed values for any percentile of the distribution in a specific storm. Uncertainty in the coefficient of variation of the site-averaged settling velocity distribution (95% confidence interval) is smaller, but still appreciable (about a factor of 5).
- No significant differences between site-to-site mean distributions have been identified. The within-site variability is on the same order as potential site-to-site differences.
- Assuming the data available for analysis are representative, the foregoing indications, with regard to storm-to-storm and site-to-site differences, support the pooling of all available data to define "typical" characteristics of particle settling velocity distributions in urban runoff, and the assumption that such results are generally transferrable to other urban runoff sites. Appendix Figure A-5 illustrates best estimates (at present) for the distribution of particle settling velocities in urban runoff from any site. For the calibration tests and subsequent projections, computations are performed for five size fractions having the following average settling velocities (based on the distribution shown by Figure A-5):

Size Fraction	% of Particle Mass in Urban Runoff	Average Settling Velocity (ft/hr)
1	0 - 20%	0.03
2	20 - 40%	0.3
3	40 - 60%	1.5
4	60 - 80%	7.
5	80 - 100%	65.

4.3.2 NURP Performance Results

A total of thirteen detention basins were monitored by various NURP projects. Of these, nine may be classified as "wet basins," which maintain a permanent pool of water. Performance characteristics of these basins have been analyzed and used to compare observed removals to those predicted using the methodology described earlier.

The detention basins studied under the NURP program encompass a wide variety of physical types. They include oversized sections of a storm drain installed below street level (Grace Street sites), ponds or small lakes on streams which drain urbanized areas (Unqua Pond, Lake Ellyn), flood control basins (Traver), a converted farm pond (Westleigh), and a golf course pond through which storm drains from an adjacent urban area were routed (Waverly Hills site). In spite of this diversity, these different detention devices may be compared by the ratio of the size of the device relative to the connected urban drainage area, and the magnitude of the storms which are treated.

Table 1 summarizes such size relationships for the NURP basins, which are arranged in order of increasing performance expectations. Based on the analysis presented in the previous section, one should expect that lower overflow rates (QR/A) and higher volume ratios (VB/VR) would tend to produce better removal efficiencies by sedimentation. Therefore, these ratios are used in Table 1 as qualitative indicators of performance. The wide range provided by the NURP data set is apparent. Basin #1 has an average overflow rate during the mean storm of about six times the median settling velocity (1.5 ft/hr) of particles in urban runoff. Further, less than 5% of the mean storm volume remains in the basin after the event, to be susceptible to additional removal by quiescent settling. At the other end of the scale, the mean storm displaces only about 10% of the volume of Basin #9, and the average overflow rate is a small fraction of the median particle settling velocity.

Table 2 summarizes the observed overall average performance of the NURP detention basins over all monitored storms. Removal efficiency is determined from the sum of pollutant masses entering and leaving the device for all storms. At some sites, there were an appreciable number of events for which monitoring data were only available for either inflows or outflows. In such cases, a reduced data set (consisting of only those events for which both inlet and outlet data were available) was used in the computation. The qualitative indications of relative performance suggested by the ranking (based on size) are supported by the tabulated results. However, the variability in actual performance results tends to confuse the picture somewhat, such that the performance relationships may be better seen in the illustrations presented in the following section.

4.3.3 Calibration Results

The probabilistic methodology was used to compute the expected removal by sedimentation of a number of pollutants. The surface area and volume of each of the nine detention devices was determined from the project reports. The statistics (mean and coefficient of variation) of runoff flow rate and volume were computed from monitoring data for storms entering the basin. A value of n = 3 was arbitrarily assigned for the shortcircuiting factor for all of the analyses which follow.

Table 1. SIZE RELATIONSHIPS FOR NURP DETENTION BASINS (BASED ON MONITORED STORMS)

			Detention Basin Size		
			Relative to Mean Monitored Storm		
Code No.	Project and Site	Approx. Average Average Basin Depth (Ft)	Overflow Rate QR/A (ft/hr)	Volume Ratio VB/VR	Relative to Size of Urban Catchment (Surf Area/Drain Area X 100%)
1	Lansing Grace Street N.	2.6	8.75	0.045	0.0095%
2	Lansing Grace Street S.	2.6	2.37	0.17	0.035%
3	Ann Arbor Pitt-AA	5.0	1.86	0.52	0.09%
4	Ann Arbor Traver	4.1	0.30	1.16	0.31%
5	Ann Arbor Swift Run	1.5	0.20	1.02	1.15%
6	Long Island Unqua	3.3	0.08	3.07	1.84%
7	Washington, D.C. Westleigh	2.0	0.05	5.31	2.85%
8	Lansing Waverly Hills	4.6	0.09	7.57	1.71%
9	Northern Illinois Lake Ellyn	5.2	0.10	10.70	1.76%

TABLE 2. OBSERVED PERFORMANCE OF WET DETENTION BASINS
REDUCTION IN PERCENT OVERALL MASS LOAD

Site No.	Project and Site	No. of Storms	Size Ratios		Average Mass Removals - All Monitored Storms (Percent)									
			QR/A	VB/VR	TSS	BOD	COD	TP	Sol.P	TKN	NO_{2+3}	T.Cu	T.Pb	T.Zn
1	Lansing Grace St. N.	18	8.75	0.05	(-)	14	(-)	(-)	(-)	(-)	(-)	(-)	9	(-)
2	Lansing Grace St. S.	18	2.37	0.17	32	3	(-)	12	23	7	1	(-)	26	(-)
3	Ann Arbor Pitt-AA	6	1.86	0.52	32	21	23	18	(-)	14	7	•	62	13
4	Ann Arbor Traver	5	0.30	1.16	5	(-)	15	34	56	20	27	•	•	5
5	Ann Arbor Swift Run	5	0.20	1.02	85	4	2	3	29	19	80	•	82	(-)
6	Long Island Unqua	8	0.08	3.07	60	(TOC=7)		45	•	(-)	(-)	•	80	•
7	Washington, D.C. Westleigh	32	0.05	5.31	81	•	35	54	71	27	•	•	•	26
8	Lansing Waverly Hills	29	0.04	7.57	91	69	69	79	70	60	66	57	95	71
9	NIPC Lake Ellyn	23	0.10	10.70	84	•	•	34	•	•	•	71	78	71

Notes: (-) Indicates apparent negative removals.

• Indicates pollutant was not monitored.

Because of the wide variability in particle settling velocities, and their important effect on removal by sedimentation, independent removal efficiency computations were performed for separate size fractions and results combined for the overall removals indicated. All five size fractions (Section 4.3.1) were assigned for TSS, total lead, and total P computations. For the other heavy metals (Cu, Zn), for TKN, and for BOD and COD, it was assumed that there would be no significant association with the largest size fraction, and computations were performed using four size fractions.

Most analyses of pollutant concentrations measured the total quantity, and did not distinguish between soluble and particulate fractions. Sedimentation computations are based on the particulate or settleable fraction. However, overall removal is expressed in terms of total quantities of pollutant, which is both the most relevant way to express results for control decisions as well as the basis for reporting observed results to be used for comparison with computations. For the analysis, therefore, it is necessary to assign the fraction of the total concentration or load which is settleable. For TSS, total P, and total lead, there is a reliable basis for doing so. Suspended solids are particulates by definition. Data developed through the NURP program indicate that lead consistently exhibits very high particulate fractions. Thus, although no specific measurements of soluble and particulate forms were made at detention basin sites, a particulate fraction of 0.9 can be assigned to lead with confidence. All but one of the sites (Basin #6) monitored both total and soluble phosphorus, and the actual particulate fraction for the site was used in the computation. A settleable fraction of 0.6 was assigned for Basin #6, guided by results from the entire NURP data base.

For these three pollutants, for which reliable estimates of particulate fractions are available and for which a significant fraction of the total is settleable, the comparison between observed removal efficiency and removals computed by the methodology described earlier is presented in Figure 10. There are a few obvious outliers; however, in general, predictions are within 10% to 15% of observed performance results. Additional confidence is derived from the fact that both observed and computed results span the entire range of performance possibilities, from less than 5% to 10%, to 90% or better.

Four significant outliers were identified and investigated. In all cases, actual monitored percent removal was much less than that projected.

- Site #4 (see Table 2) shows almost no TSS removal, although a substantial (~60%) removal is projected. At this newly installed basin, the project report indicates that significant bank erosion at the outlet structure occurred during the test program. Lead was not monitored, but observed/predicted Total P removals compare quite favorably at this site.

- Site #5 data show almost no Total P removal, although about 50% reduction is projected. On the other hand, both TSS and lead projections compare favorably with observed data. The basin is a shallow, vegetated area, characterized by the local project as a wetland. The possibility of the basin outlet discharging phosphorus from internal sources, rather than influent runoff, is suggested.

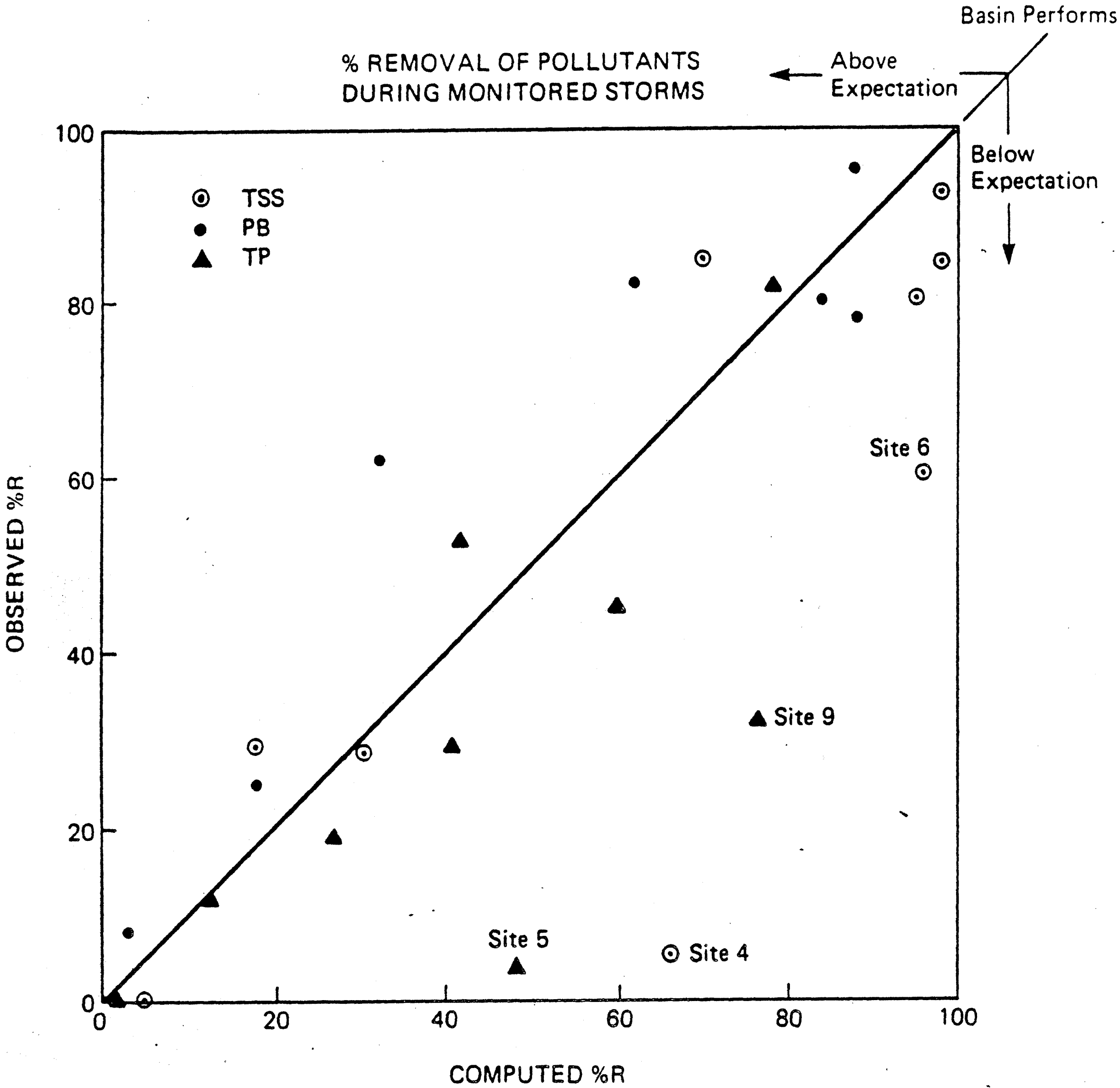


Figure 10. Comparison of observed vs. computed removal efficiencies (site numbers given for outliers—see text)

- Site #9 shows Total P removal projections that are significantly in excess of observed removals. However, as with Site #5, projected removals compared quite favorably with observed performance for both lead and TSS. This rather large basin, actually a five-acre lake, supports significant algal growth. The observed significant reductions for soluble phosphorus and nitrogen are attributed to algal uptake, since they could not have resulted from sedimentation.

  Conversion of soluble nutrients to algal cells would tend to add a source of TSS and Total P to basin outflows that are not associated directly with the particulate forms entering with the stormwater. Such processes tend to reduce the apparent sedimentation efficiency.

- Site #6 is a natural pond (with surrounding park) in a stream system draining an urban area, and it supports an appreciable population of ducks fed by local residents. Lead and Total P removals compare favorably to projections. Removal of TSS is appreciably less than projected. A comprehensive analysis of removal efficiency for coliform organisms was conducted at this site. This was not incorporated into the methodology calibration due to the lack of similar data at other sites. It is instructive to note, however, that despite the duck population, average removals for the monitored storms were on the order of 90% for total coliforms, fecal coliforms, and fecal strep.

4.4 EXAMPLE COMPUTATION

A. Given

A 10-acre residential development has a runoff coefficient (Rv) estimated at 0.25. All stormwater runoff from the area is to be routed to a wet pond detention basin.

Space constraints limit the basin dimensions to 25 by 50 ft, or a surface area of 1250 square feet. The basin will have an average depth of 4 feet. Physical storage volume is 5000 cubic feet (CF).

Rainfall statistics for the area are:

			mean	coef. of variation
Volume	(V)	inch	0.53	1.44
Intensity	(I)	in./hr	0.086	1.31
Duration	(D)	hr	7.2	1.09
Interval	(Δ)	hr	85.0	1.00

Particle settling velocities as tabulated in Section 4.3.1 are assumed to apply for this site.

B. Required

Estimate the long-term average reduction in total suspended solids (TSS) in storm runoff that can be obtained from the specified basin size.

C. Procedure

Step 1 - Select appropriate performance curve to use.

- Figure 1 does not apply because removal efficiency by sedimentation varies with flow through rate, as illustrated by Figures 7 and 8
- Figure 2 applies for removal under dynamic conditions
- Figure 3 and 4 apply in this case because storage capacity is provided by the device, and removal by sedimentation also occurs during quiescent conditions between storm events

Step 2 - Compute runoff parameters for mean storm - flow rate (QR) and volume (VR).

$$QR = (I) * (R_V) * (Area) * (43{,}560 / 12)$$
$$= 0.086 * 0.25 * 10 * 3630 = 780 \text{ CFH}$$

$$VR = (V) * (R_V) * (Area) * (43{,}560 / 12)$$
$$= 0.53 * 0.25 * 10 * 3630 = 4807 \text{ CF}$$

Assume that the variability of runoff parameters is the same as for the corresponding rainfall parameters.

$$CV_q = 1.31 \quad \text{and} \quad CV_v = 1.44$$

Step 3 - Compute the removal under DYNAMIC conditions.

The overflow rate during the mean storm (QR / A) is

$$QR / A = 780 / 1250 = 0.62 \text{ ft / hr}$$

Each of the selected size fractions will have a different removal efficiency at the mean flow. Use the appropriate settling velocity in equation (8), or scale from Figure 8 to estimate R_M, the removal at the mean oveflow (QR / A = 0.62).

Fit a straight line approximation for each removal curve in Figure 8 so that it intersects the exact curve at the mean overflow rate (QR/A = 0.62). Estimate the removal efficiency at very low rates (Z in equation 3) from the point where the fitted line intersects the vertical axis.

Then, for each size fraction, use the values obtained above in equation (3), together with the estimate of coefficient of variation of runoff flows to estimate the long-term average removal (R_L).

Alternatively, if estimates of "Z" are 100% for all size fractions (a reasonable estimate in this case), the long-term average removals (R_L) can be scaled directly from Figure 2.

Since the size fractions are mass weighted, the overall TSS removal will be the average of the five size fractions.

Results using the graphic approach are as follows:

Size Fraction	Average Settling Velocity (ft/hr)	R_M (%) (Fig. 8)	R_L (%) (Fig. 2)
1	0.03	5	5
2	0.3	40	23
3	1.5	90	77
4	7.	100	100
5	65.	100	100

OVERALL AVERAGE REMOVAL = 61

fraction NOT removed $f_D = (100 - 61) / 100 = 0.39$

Step 4 - Compute the removal under QUIESCENT conditions.

Basin Volume ratio (VB / VR)

$$(VB / VR) = 5000 / 4807 = 1.04$$

The long-term average removal efficiency is defined by Figure 3. This is based on the coefficient of variation of runoff volumes (estimated at 1.44 in Step 2) and the "Effective" Volume ratio (VE/VR), rather than the volume ratio computed immediately above, which is based on physical size of the basin.

The desired ratio (VE/VR) is scaled from Figure 4 using the ratio VB/VR = 1.04 computed above, and the Emptying Rate ratio.

$$E = \Delta * \Omega / VR$$

Δ is the average interval between storms = 85 hr

VR is the mean storm runoff volume = 4807 CF

Ω is the solids removal rate as defined by equation (11) in Section 4.2.2, and is the product of basin surface area (1250 sq ft) and the settling velocity (v_s).

$$\Omega = v_s A$$

Each of the five size fractions has a different settling velocity, and therefore different values for Ω, E, the effective volume ratio VE/VR, and finally the quiescent removal efficiency. The table below lists the results of the foregoing procedure for estimating removals under quiescent settling.

SIZE NO.	FRACTION Vs (ft/hr)	Ω (= Vs A)	E (= ΔΩ/VR)	VE / VR (Fig. 4)	% REM (Fig. 3)
1	0.0	38	0.7	0.50	35
2	0.3	375	6.6	1.00	54
3	1.5	1875	33.2	1.04	56
4	7	8750	154.7	1.04	56
5	65	81250	1436.7	1.04	56

OVERALL AVERAGE REMOVAL = 51

fraction NOT removed f_Q = (100 - 53) / 100 = 0 .49

Step 5 - Compute the COMBINED removal under both dynamic and quiescent conditions.

Overall removal accomplished by the combination of dynamic and quiescent processes is computed directly from the fractions NOT removed by each process.

Fraction NOT removed by quiescent settling $f_Q = 0.49$

Fraction NOT removed by dynamic settling $f_D = 0.39$

$$\% \text{ Removed (overall)} = [\,1 - (f_Q * f_V)\,] * 100\%$$

$$= [\,1 - (0.49 * 0.39)\,] * 100\%$$

$$= 81\ \%$$

A careful examination of the results is instructive. As the following summary table indicates, the quiescent process has a lesser effectiveness for the removal of particles with the higher settling velocities, compared with dynamic removals. This is not because the process provides less efficient sedimentation. It is a result of the fact that for a basin volume about equal to the mean storm runoff volume (VB/VR = 1.04), a significant percentage of storm event runoff volumes are greater than the basin capacity. The indicated quiescent removals reflect the fact that some fraction of the total runoff does not remain in the basin to undergo quiescent settling.

The efficiency and importance of the quiescent process is reflected by its significantly higher effectiveness in removing the slower settling fractions.

SIZE NO.	FRACTION Vs (ft/hr)	% REMOVAL DYNAMIC	% REMOVAL QUIESCENT	% REMOVAL COMBINED
1	0.0	5	35	38
2	0.3	23	54	65
3	1.5	77	56	90
4	7	100	56	100
5	65	100	56	100
	ALL	61	51	81

4.5 DISCUSSION

On the basis of the comparisons between observed and predicted performance (presented in Figure 10) the analysis methodology described earlier appears to provide sufficiently reliable estimates of performance for use in planning activities. More refined computations, which do not require some of the approximations and assumptions used in the probabilistic methodology, are certainly possible. SWMM and some other deterministic models have this capability, and it would be interesting and useful to compare projections. It should be noted however, as a close scrutiny of observed performance (Table 2) will indicate, that because of either limited data sets or complex site-specific factors, or both, actual observed performance does not conform to a consistent pattern. It is suggested that other, more refined computations are likely to reflect similar levels of uncertainty when compared with actual performance data.

The discussion of the outliers in the comparison between observed and computed performance serves two purposes. First, by identifying site factors that can reasonably be expected to cause anomalous results, it adds credibility to the analysis methodology. Second, it highlights the fact that competing processes are at work in wet pond detention basins that may enhance or degrade removal of specific pollutants.

It is tempting to consider an extension of this methodology (or other analysis methodologies) to incorporate biological or other processes that are also obviously at work in at least some stormwater detention basins. The available data were considered inadequate to support a meaningful extension of the analysis at this time, although the means for doing so are clear. Biological or other decay mechanisms are typically expressed as rate coefficients with units of the reciprocal of time (e.g., 1/day). Such rates, for which reasonable estimates can be derived from the literature or specific studies, can be converted to a psuedo-settling velocity (or vice-versa per equation 10). With additional data, this would be a worthwhile effort due to the significance of mechanisms other than sedimentation in stormwater basins.